

# E298A/EE290B

## Introduction to Electron Beam Lithography & Nanofabrication Technology

Dr. Erik H. Anderson & Dr. J. Alexander Liddle

Materials Sciences Division, Lawrence Berkeley National Laboratory

Lectures: Tuesdays, 2:00 pm – 3:30 pm

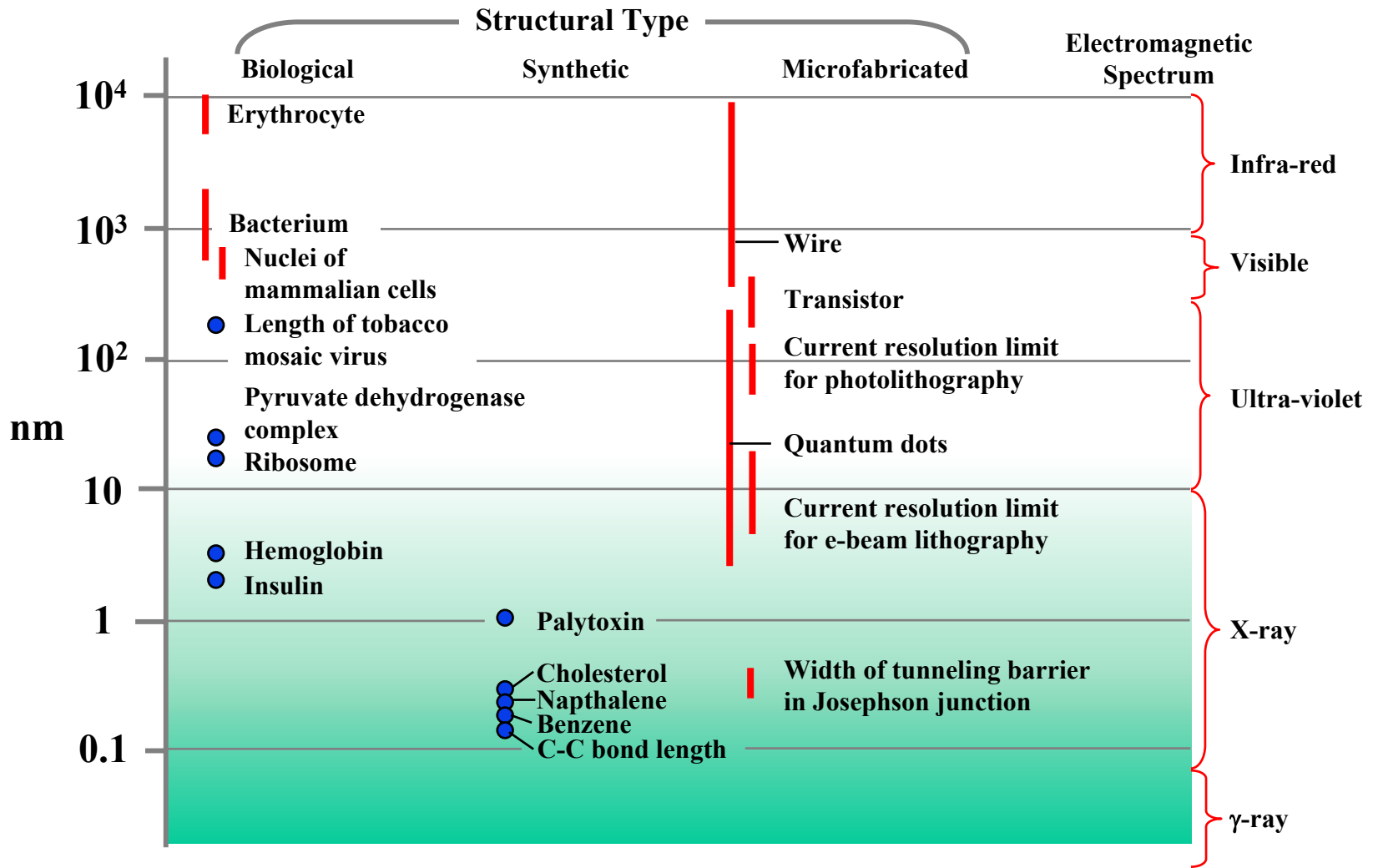
65 Evans Hall, UC Campus

Lab: Thursdays 3:00 pm – 5:00 pm

Bldg. 2, Rm. 137, LBL



# The Scale of Things



After Whitesides et al. *Science*, **254** 1312 (1992)



# Contact Information

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- Alexander Liddle
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  - [jaliddle@lbl.gov](mailto:jaliddle@lbl.gov)
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  - 510 495 2383
  - [AEsakdinawat@lbl.gov](mailto:AEsakdinawat@lbl.gov)
- Lab, LBL Building 2 room 137
  - 510 486 4332



# Course Details



- *Homework:* Weekly assignments due at the beginning of the Thursday lab session
- *Report:* A written term paper will be required. An experimental project will be required. An oral presentation of paper to class will be required.
- *Grading:* Grades will be based on the weekly homework and term paper
  - Homework – 30%
  - Project Proposal – 20%
  - Project Report – 40%
  - Project Presentation – 10%



# Expectations



- Homework
  - Handed out at Tuesday classes, due at start of the lab session on the following Thursday.
  - Assume access to Mathematica, MatLab etc.
- Lab
  - Starts *promptly* at 3:00 pm
  - Shuttle buses run approx. every 10 mins
  - Passes required - will be e-mailed
- Lectures
  - Interactive!



# Project Guidelines I



- A project is required for the class and is expected to be a substantial part of the learning experience. The scope of the project should be realistic and take into account the limitations in time and materials. The project should explore a scientific application where electron beam lithography is needed to achieve a result, or the electron beam lithographic process itself. The project will consist of a written proposal, which must describe the planned experiments together with a suitable schedule. The proposals will be reviewed to make sure that the scope is appropriate. The project milestones are expected to be followed. A written report of the project results and a formal presentation to the class are required.
- Proposals due Tuesday, February 17<sup>th</sup> - we will review the proposals individually on February 12<sup>th</sup>
- The report is due Tuesday, May 3<sup>rd</sup>
  - The report should be formatted in the style of a JVST paper, 4-6 pages in length. Each journal page is approx. 900 words, and each figure is equivalent to 200 words
- Class presentations will be on Thursday May 5<sup>th</sup>, which will be the last day of class. Each presentation will be 15 minutes long in the style of a conference talk.
  - Allow 1 minute per viewgraph and 2 minutes for questions



# Project Guidelines II

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- The work at LBL will be under the supervision of E.H. Anderson and J.A. Liddle
- The project can be related to the thesis work of the student, but should not be in the critical path!
- The project should use readily available materials and processes to the fullest extent possible. Health and safety issues may restrict materials and processes – investigate these possibilities early
- Samples for e-beam lithography can be on 1 – 8” wafers and quartz plates. No fragments!
- Data sets can be generated at LBL or with any CAD system that produces a suitable GDSII file
- Start prototyping and process development early!
- Plan something that will be instructive and fun



# Project Hints



- The voice of experience....
  - How hard could it be....?
  - What could possibly go wrong....?
- Keep the project scope simple, focused and reasonable. Estimate what you think you can do, and divide by two, focusing on the critical elements. This is a class project and not a thesis!
- Start early! Experimental efforts always take longer than expected, even when you know that experimental efforts always take longer than expected (yes, this is recursive!). Lots of things can go wrong in the lab, and often do. Remember, if you can't imagine how something could fail, it just shows a lack of imagination!
- Don't reinvent the wheel – if someone has already gone to the trouble of developing a process, use it!
- The written proposal is only a plan and "no plan survives contact with the enemy". Be prepared to update your plan in light of experience.





# Course Outline

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1. Introduction - EHA/JAL
2. Patterning Technology - JAL
3. Fundamentals of E-Beam Systems I - EHA
4. Data Fracturing and Processing - EHA
5. Proposal Presentations to Class
6. Electron Interactions in Solids - JAL
7. Fundamentals of E-Beam Systems II - EHA
8. Nanofabrication Characterization I - JAL



# Course Outline

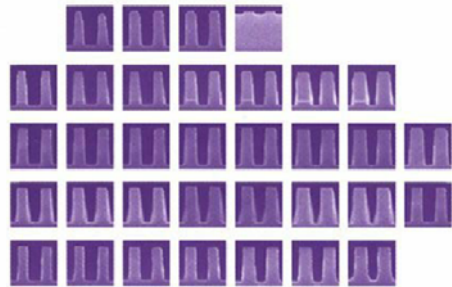
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- 9. Resist Materials I - JAL
- 10. Resist Materials II - JAL
- 11. Proximity Effect and Correction - EHA
- 12. Pattern Transfer Techniques I - JAL
- 13. E-Beam Writing Strategies - EHA
- 14. Project Presentations*



# Recommended Textbooks



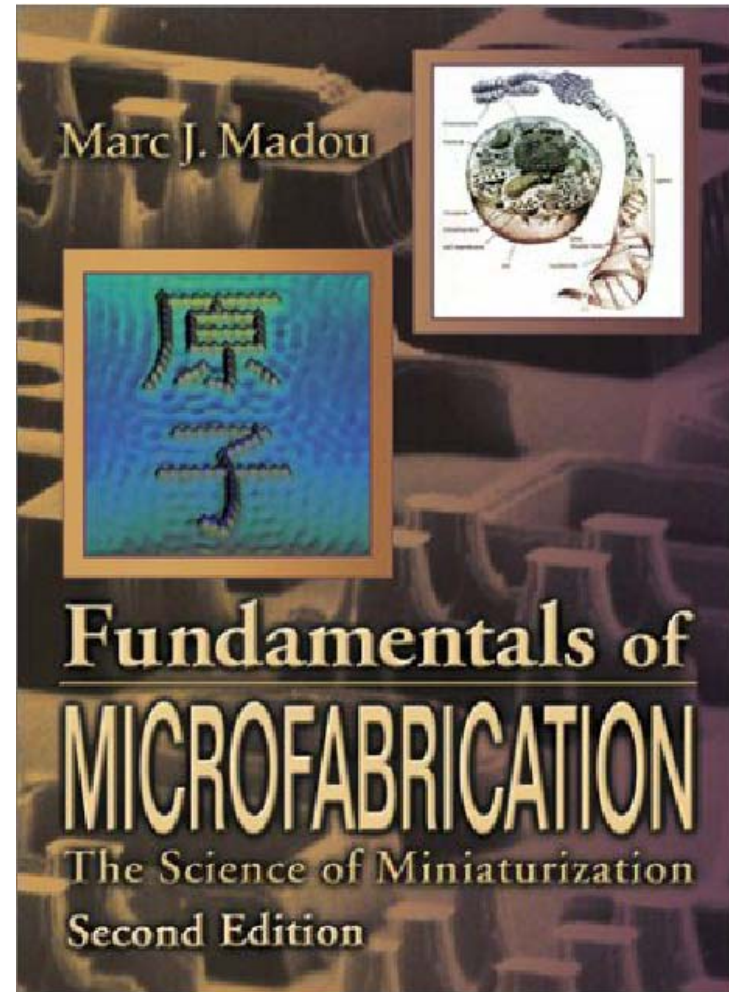
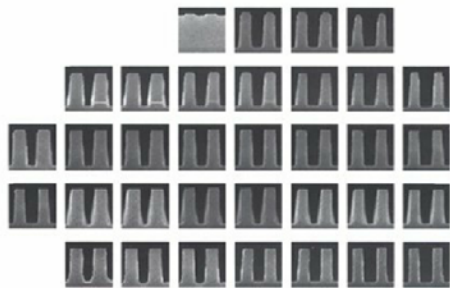
## MICROLITHOGRAPHY

Science and Technology

edited by

James R. Sheats

Bruce W. Smith



# Suggested Reading

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- *Microlithography, Micromachining and Microfabrication* – P. Rai-Choudhury
- *Introduction to Microlithography* – L.F. Thompson, C.G. Willson and M.J. Bowden
- *Microsystem Design* – Stephen D. Senturia
- *Scanning Electron Microscopy* – Ludwig Reimer
- *Micro-Optics* – Hans Peter Herzig, Ed.
- *Signs of Life* – Ricard Solé & Brian Goodwin
- *The Diamond Age* – Neal Stephenson



# After Taking This Course....

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- You should have a basic understanding of the complete sequence in the nanofabrication process from CAD through to fabricated structure including basic metrology and characterization
- You will have completed a project and presented it professionally to your peers
- You should be familiar with the current state-of-the-art and inspired to improve it!



## 2003 Class Projects

Daewon Ha:-	<i>Impact of Alignment-Mark on Statistical Alignment Accuracy in E-beam lithography (<a href="#">Paper at MNE2003</a>)</i>
Garth Robins:-	<i>Pattern and Probe-based Aberration Monitors for the Human Eye</i>
Gregory McIntyre:-	<i>Direct-Write of Phase-Shifting Mask to Characterize Optical Lithography Illumination</i>
Jeremy Robinson:-	<i>Nanocatalyst Fabrication Using a Stencil Mask (<a href="#">LDRD 2003</a>)</i>
Kyoungsub Shin:-	<i>Process Optimization for AZPN/HSQ Bilayer Resist E-Beam Lithography: Effects of PAB and Development Time</i>
Varadarajan Vidya:-	<i>Sub-20 nm Gate Definition for MESFET/MOSFET IC Applications</i>
Sriram Balasubramanian:-	<i>Application of E-beam Lithography to FinFET Based SRAMs</i>
Yu-Chih Tseng:-	<i>High Energy Electron Beam Lithography on Self-Assembled Monolayer of 3-aminopropyltriethoxysilane</i>



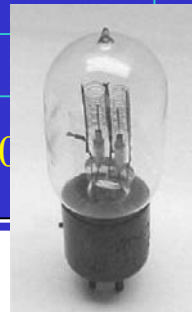
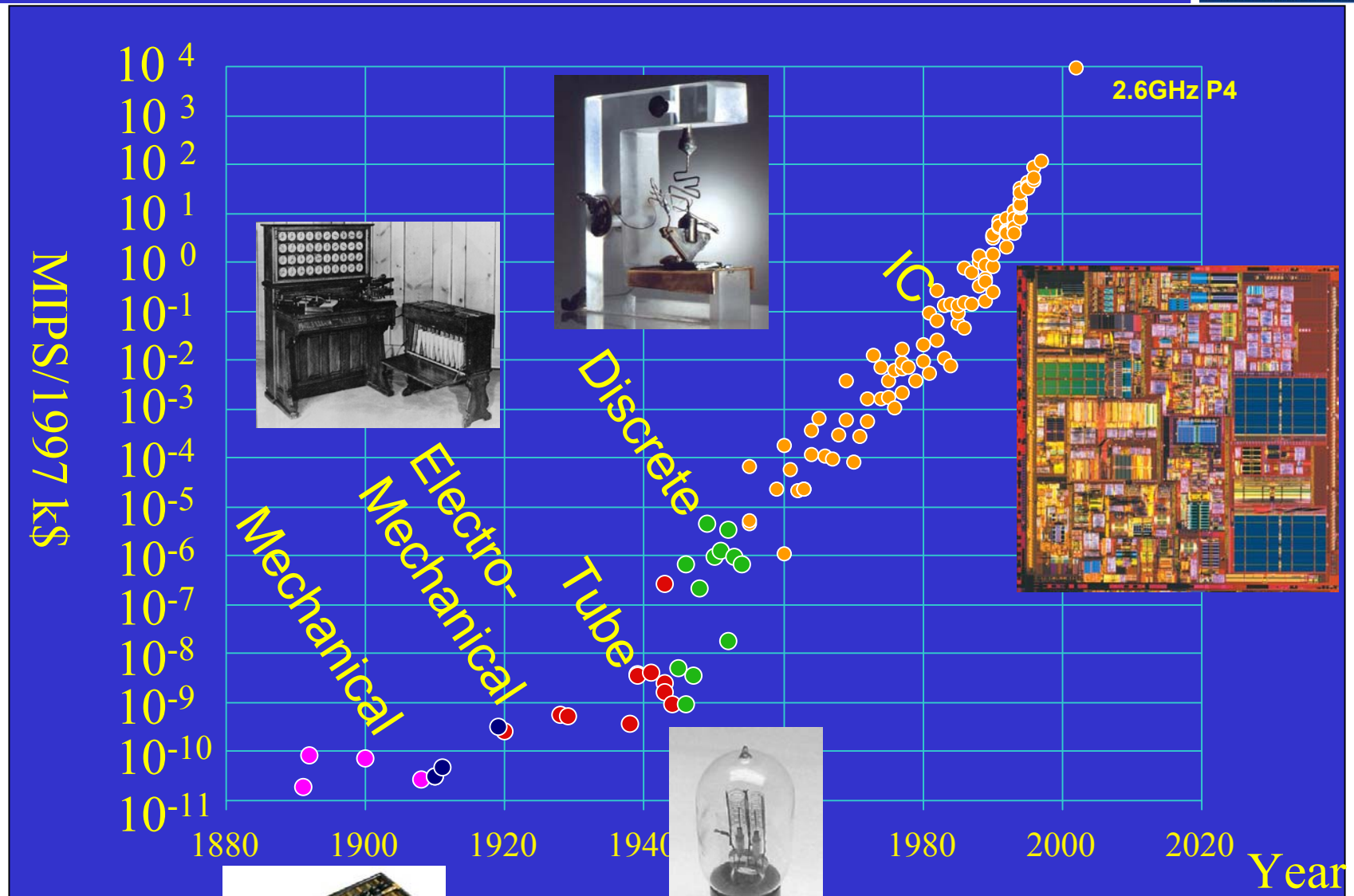
## 2004 Class Projects

Michael Huang:-	<i>Ultra Broadband and Highly Reflective Sub-Wavelength Gratings</i>
Marie Eyoum:-	<i>E-Beam Lithography Application for the Definition of Nanogaps in the Fabrication of Electrostatic Transducers</i>
Ilan Gur:-	<i>Increasing the Complexity of Capillary-Based Nanostructure Assemblies</i>
Chenghan Yu:-	<i>Nanofluidic Devices of Supported Lipid Bilayer Membranes</i>
Hiu Yung Wong:-	<i>Radiation Effects in Hafnium Oxide as MOS Gate Dielectric Caused by E-Beam Lithography</i>
Gang Liu:-	<i>Electro Optical Characteristics of Au Nanostructures Fabricated by E-Beam Lithography</i>
Danjuro Echizenya:-	<i>Nanomolding for Fabrication of a Designed CMP Pad</i>
Erik Douglas:-	<i>Iridium Oxide pH Sensor for Nanoscale Electrochemical Cell Monitoring</i>
Anne Sakdinawat:-	<i>Fabrication of Free-Standing Zone Plates for Soft X-ray Microscopy</i>



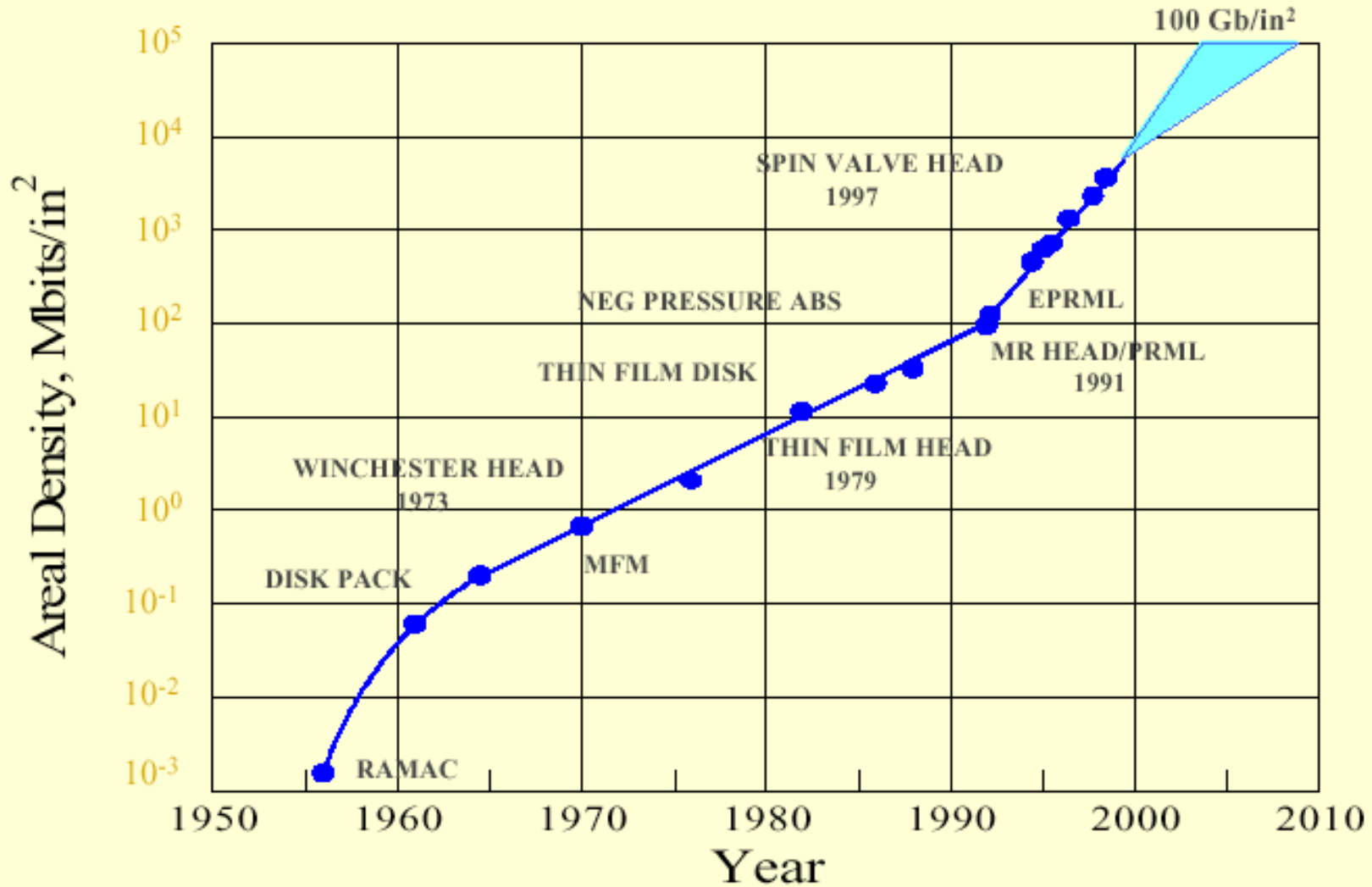


# Cost of Computing Power Versus Time

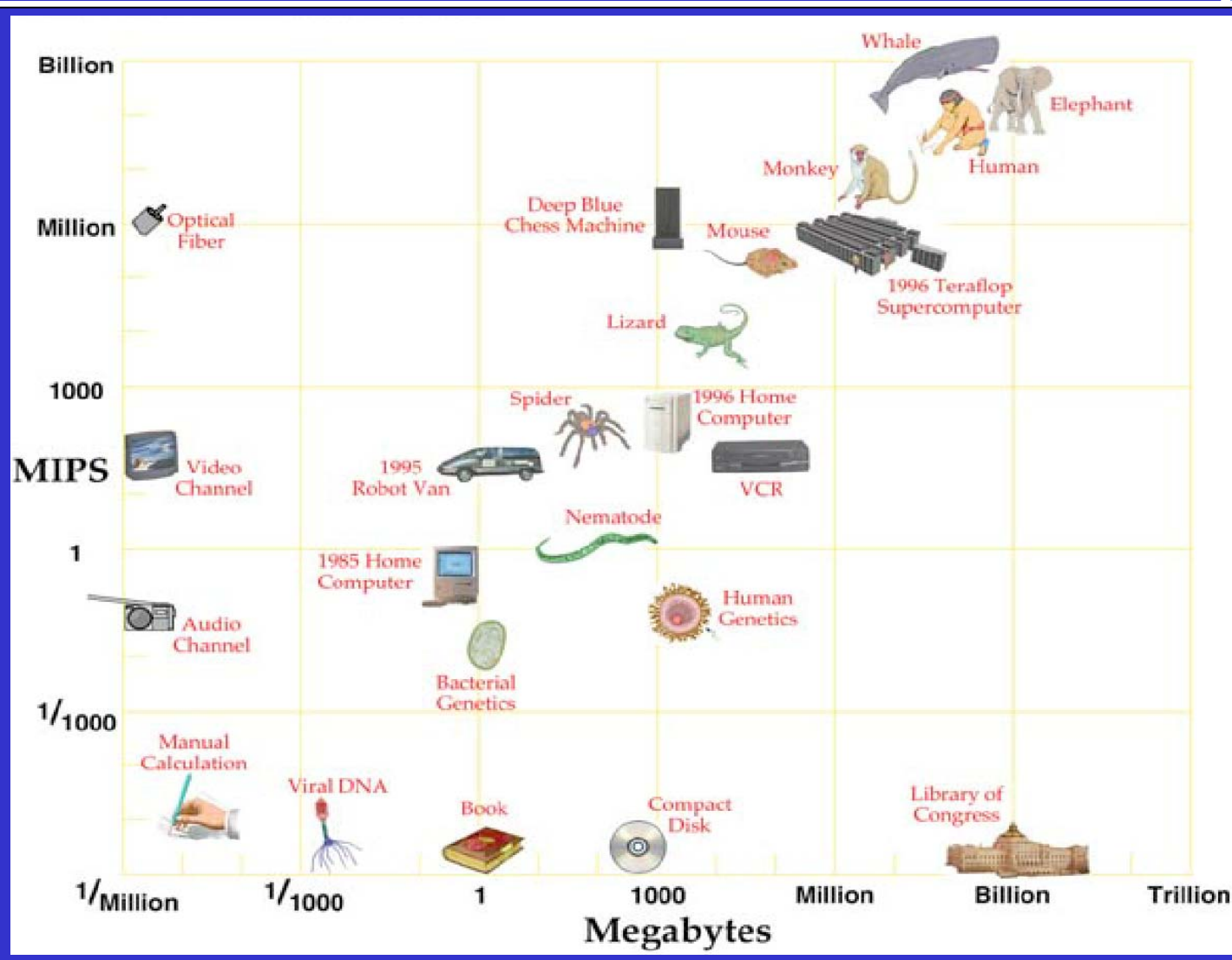




# Storage Capacity vs Time



# Evolution of Computational Power

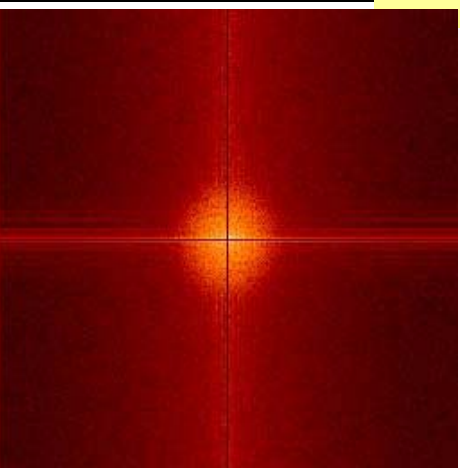
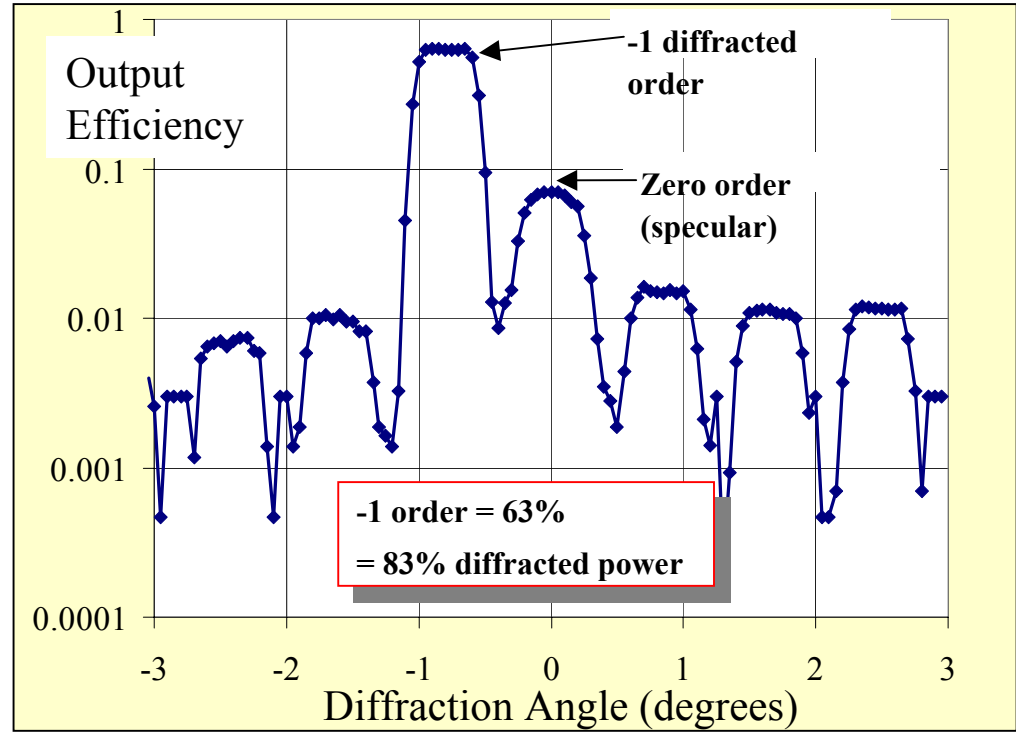
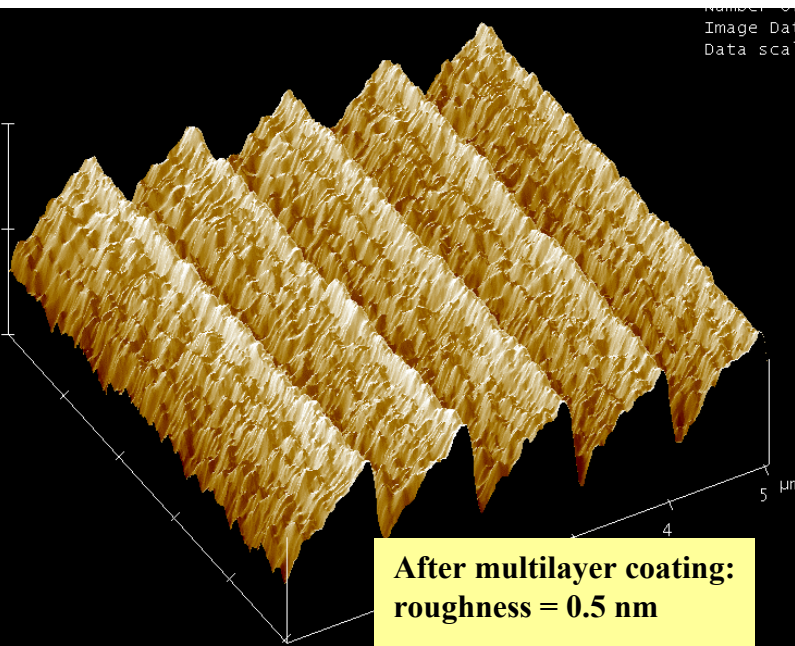


Hans Moravec, Journal of Evolution and Technology. 1998. Vol. 1

<http://www.transhumanist.com/volume1/moravec.htm>

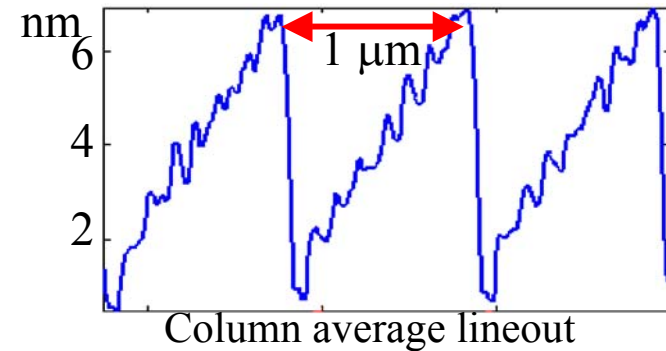


# EUV Blazed Grating

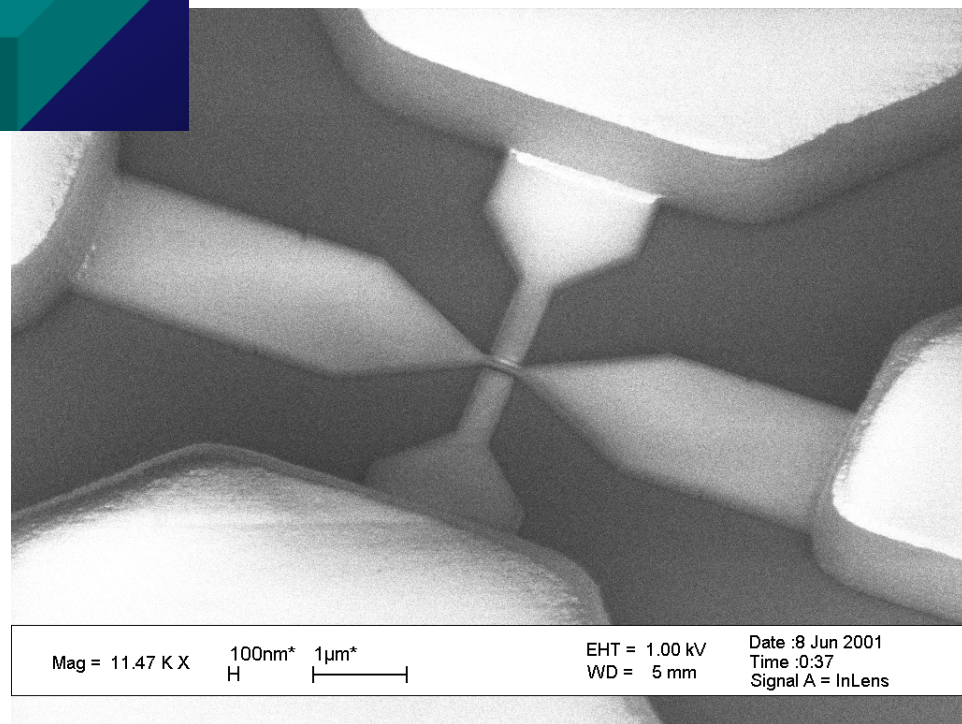
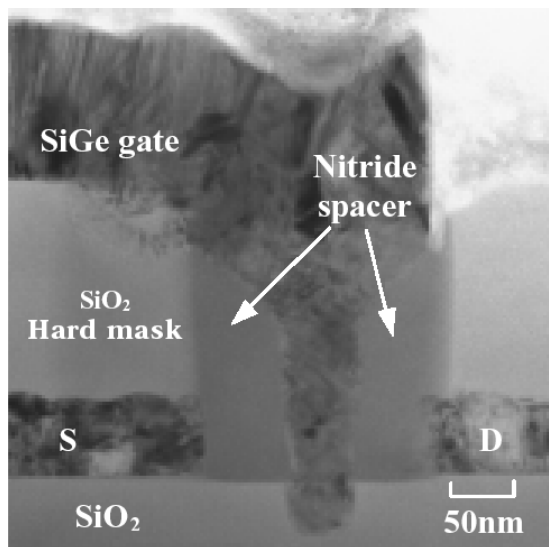
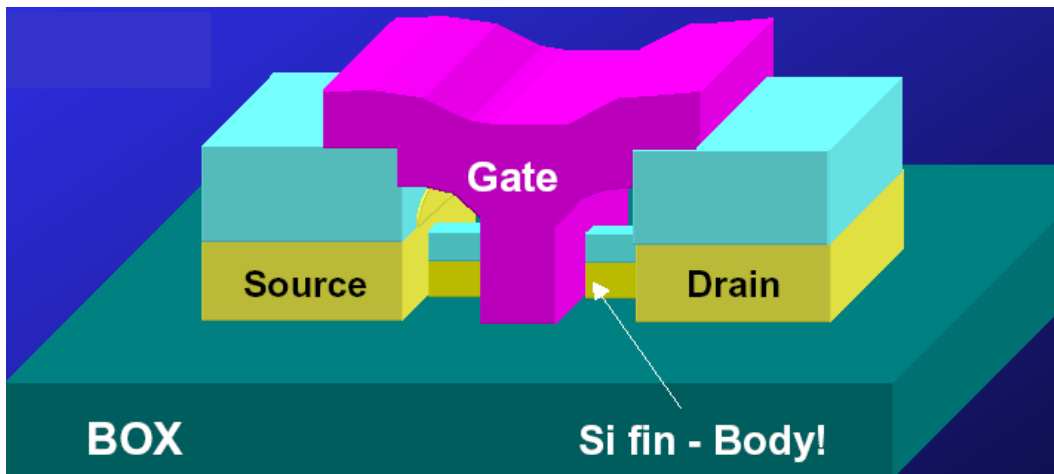


Light is scattered by surface roughness – loss in diffracted power

⇐ PSD of multilayer coated grating



# Nano-electronics LBNL/UC Berkeley



X. Huang, W.-C. Lee, C. Kuo, D. Hisamoto, L. Chang, J. Kedziersky, E. Anderson, H. Takeuchi, Y.-K. Choi, K. Asano, V. Subramanian, T.-J. King, J. Bokor, and C. Hu, "Sub-50 nm FinFET: PMOS," IEEE IEDM Technical Digest,

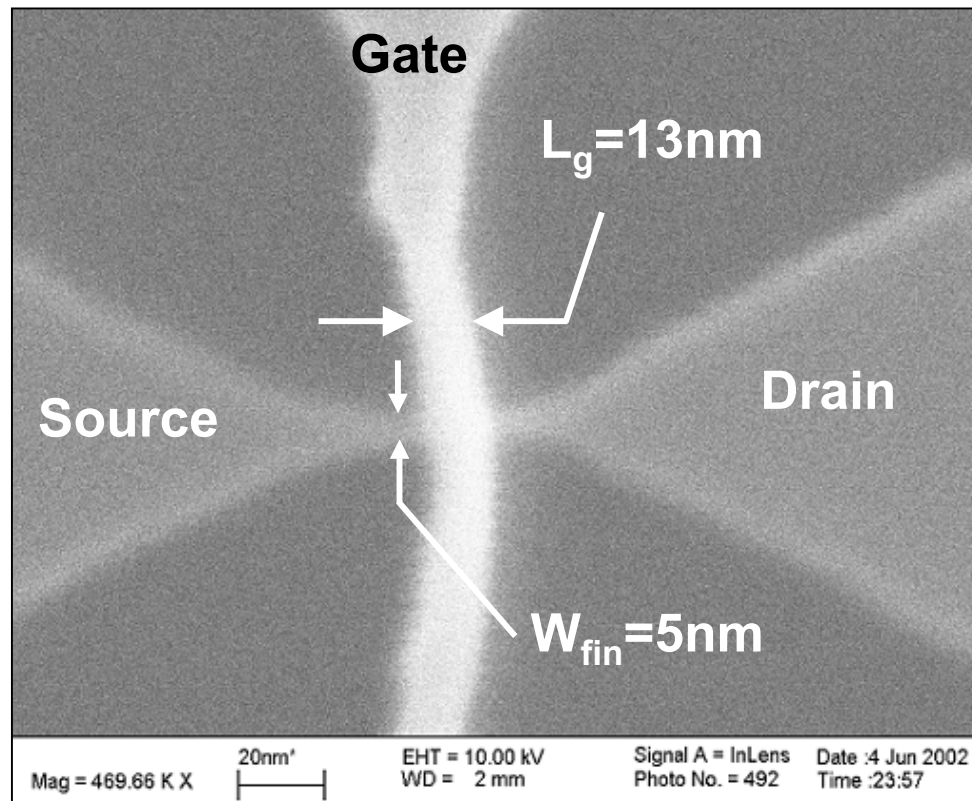
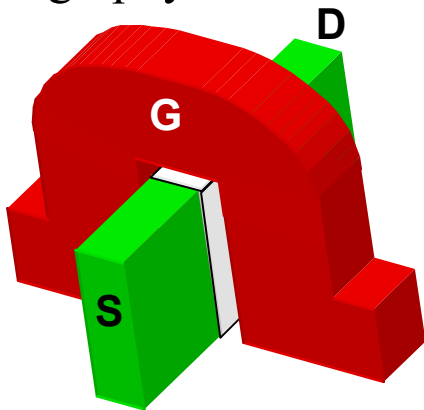




# FinFET Fabrication

What is the ultimate limit of CMOS devices?

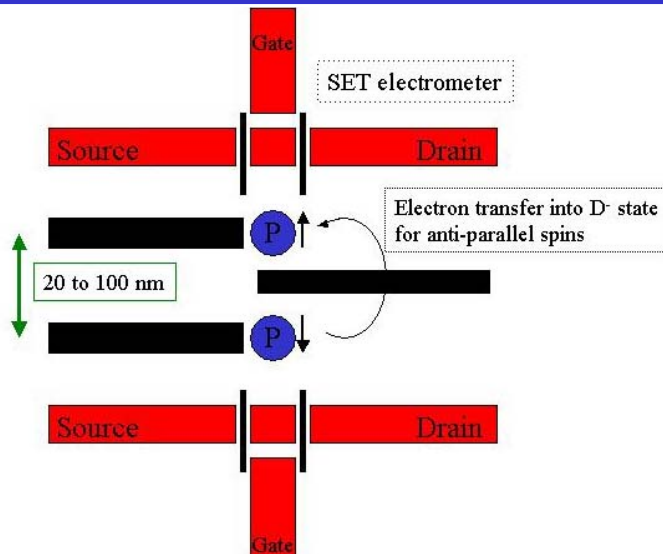
- FinFET is the most promising device structure for deep sub 100 nm device operation
  - Gate lengths down to 13nm achieved
  - Electron-beam + optical lithography



Leland Chang, Patrick Xuan, Prof. Tsu-Jae King UCB

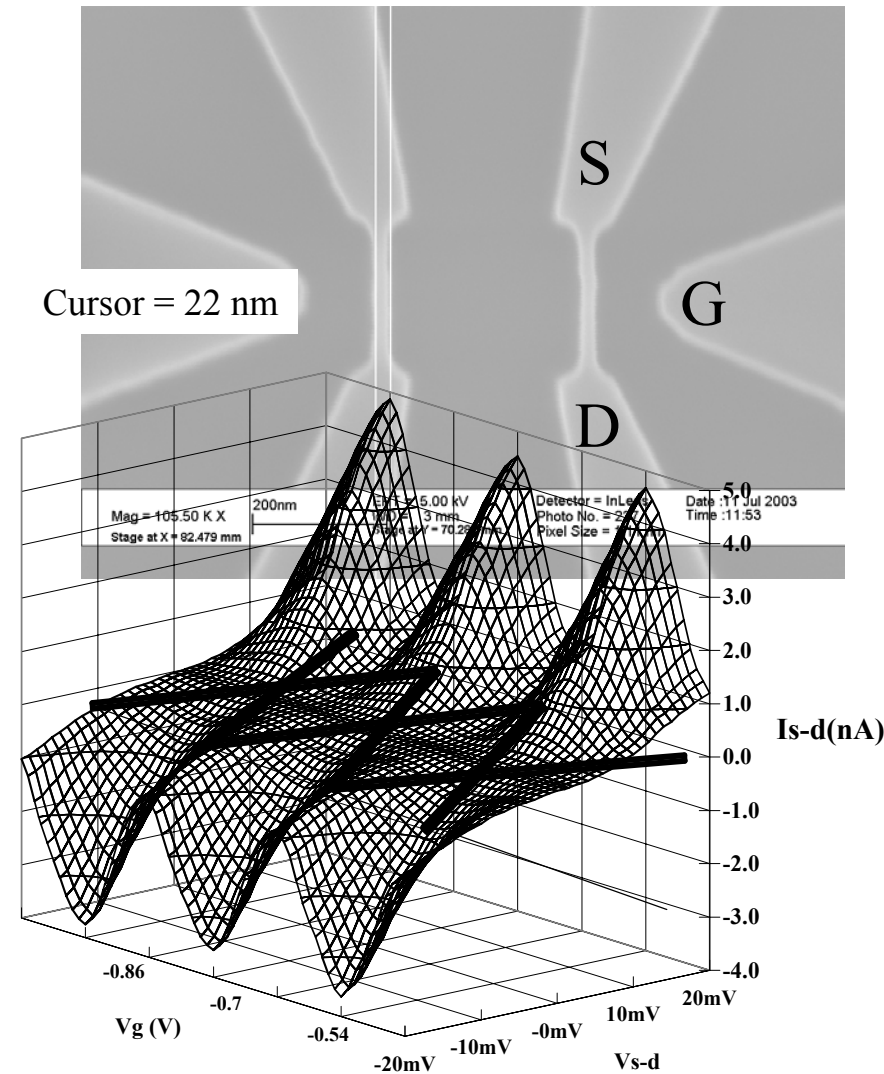


# Quantum Computing



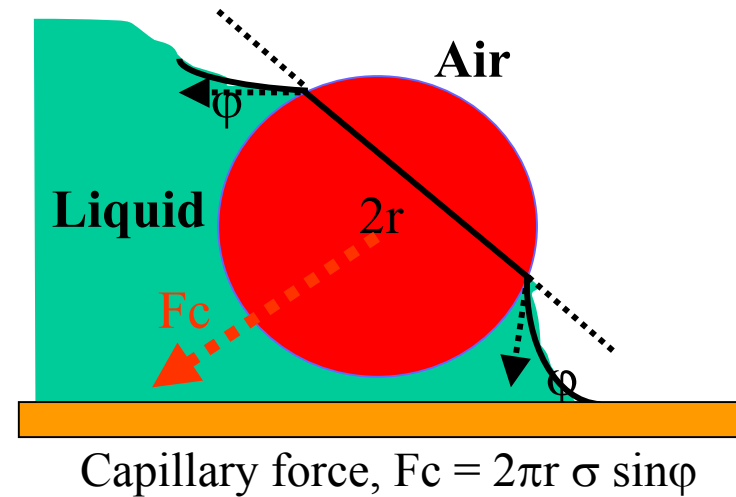
Solid-state quantum computer integrable with Si technology –

- Integration of  $^{31}\text{P}$  qubits with gates to control electron spins and SET readout structures
  - Single ion implantation
  - Electron beam lithography
  - Semiconductor processing

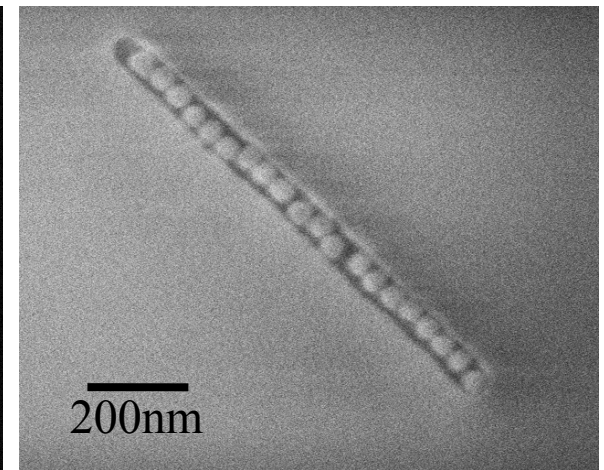
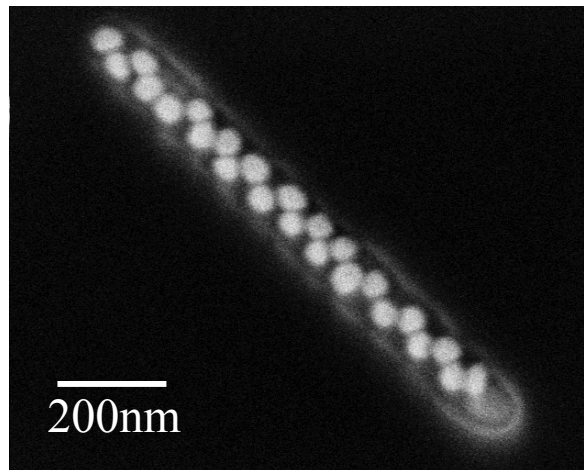
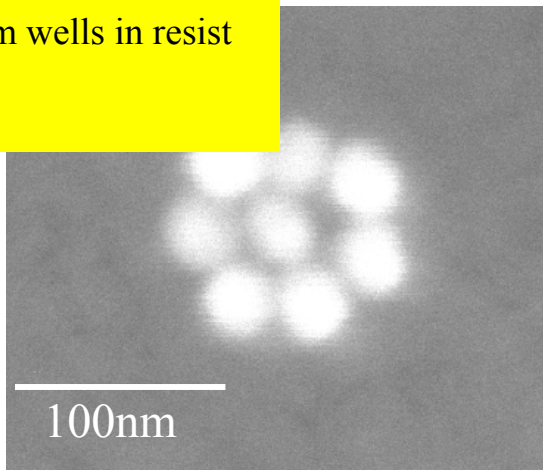


# Nanocrystal Assembly

- Nanoparticles must be assembled in a controlled fashion in order to exploit their unique properties fully
  - Microfluidics combined with nanolithography enables accurate placement of nanocrystals

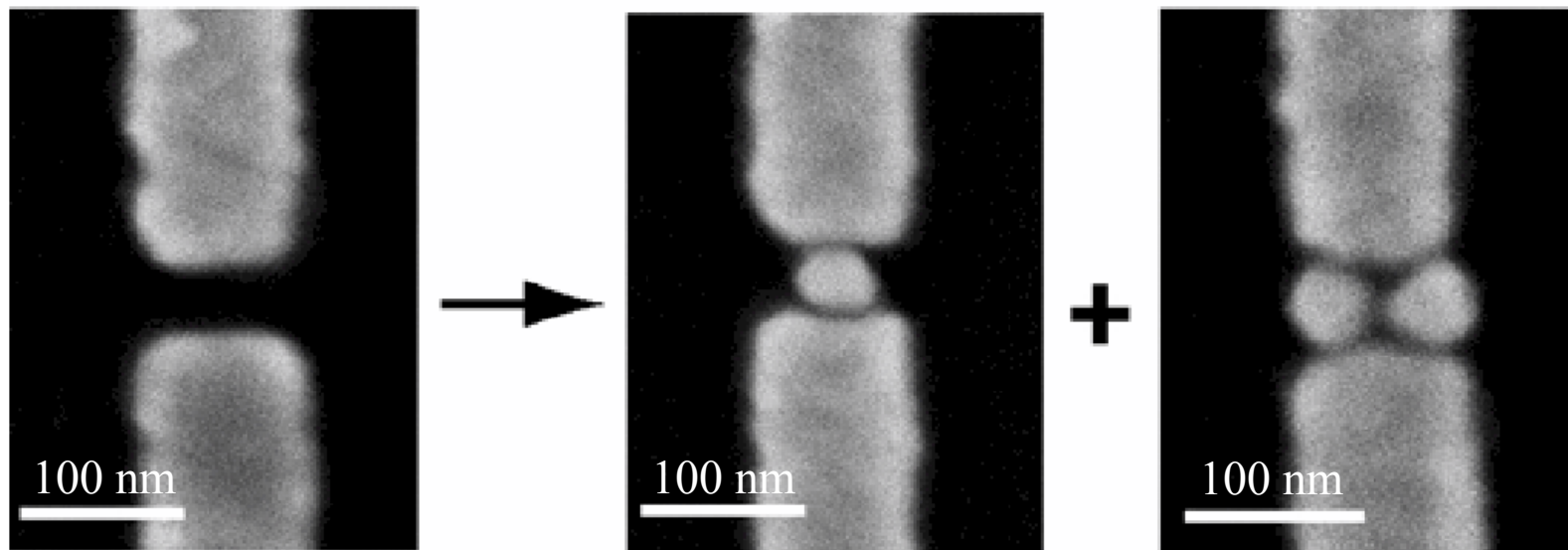


30 nm Au particles  
assembled into 100  
nm wells in resist

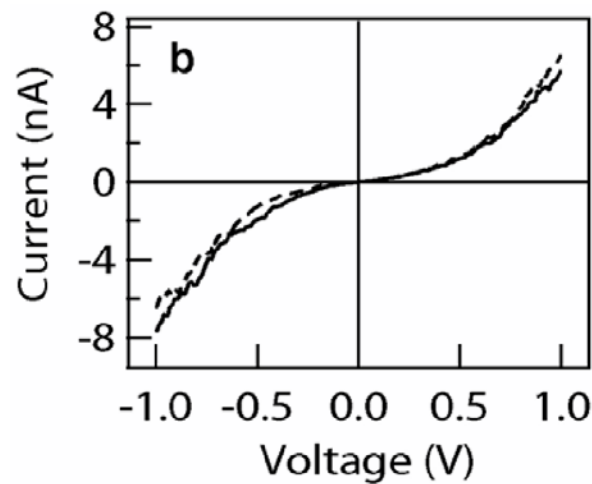


Dr. Yi Cui, Prof. P. Alivisatos, UCB

# Electrical Measurements of Nanocrystals

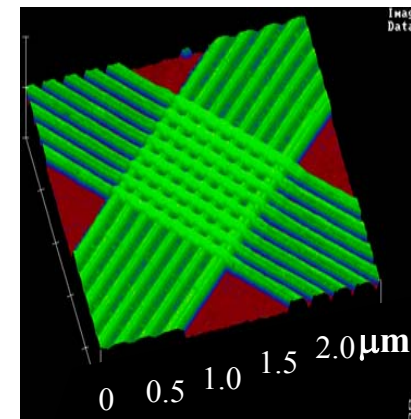
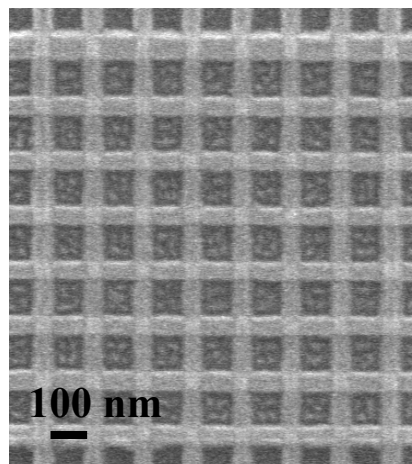
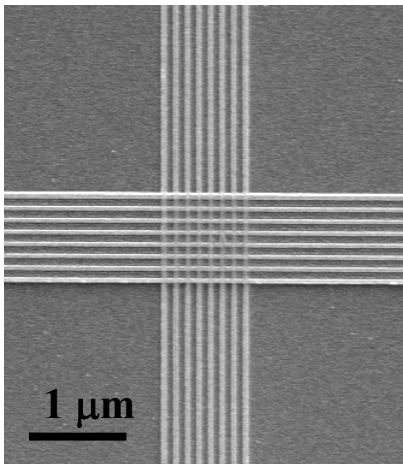
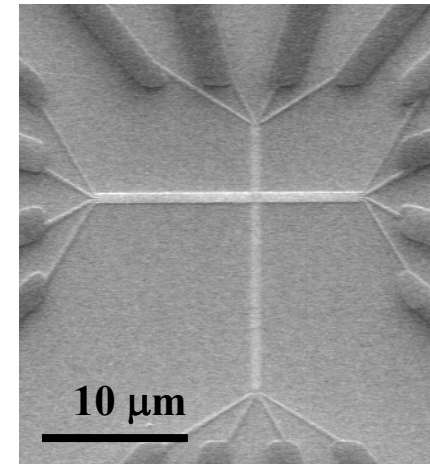
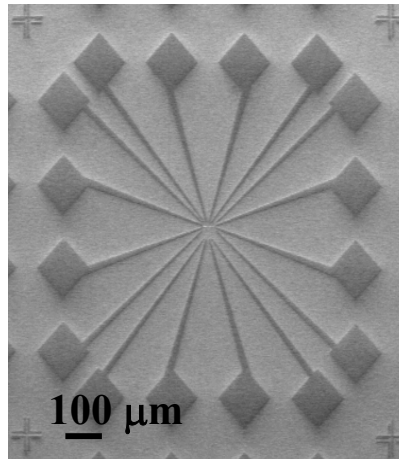
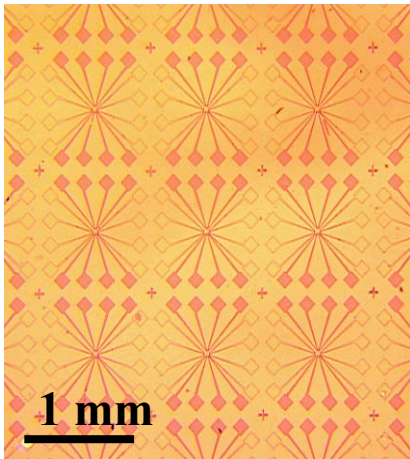


50 nm Au particles assembled between electrodes using capillary forces





# HP/LBNL Nanoimprint Mask for Molecular Electronics



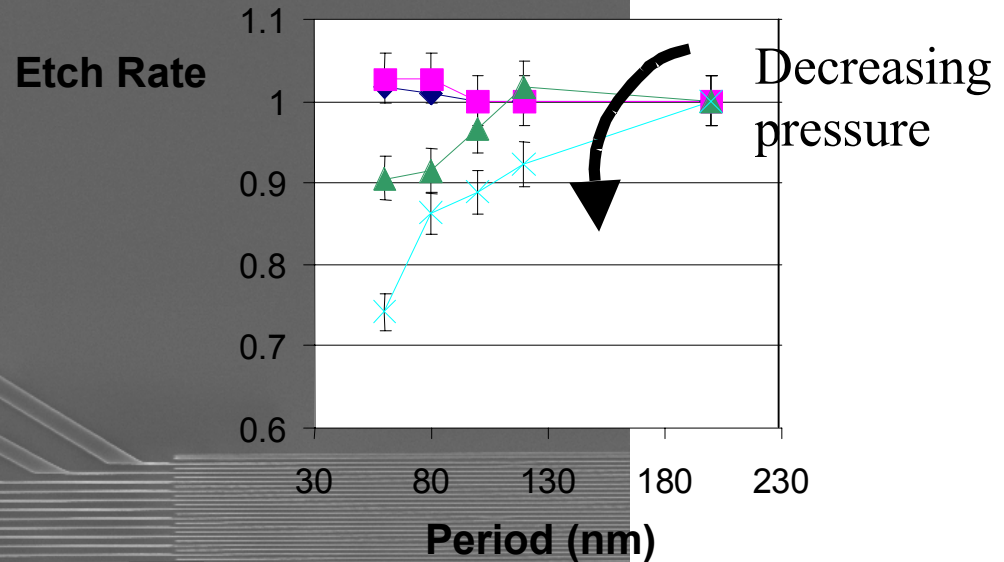
Lines formed by using bilayer as mask for HBr etching of Si

Erik H. Anderson, Deirdre Olynick, Bruce Harteneck,  
LBNL, Y. Chen H.P./UCLA



# Etching for Nanoimprint

## Normalized Etch Rate vs. Period



18 nm lines on  
60 nm period

Mag = 6.00 K X  
Stage at X = 74.943 mm

2µm

EHT = 5.00 kV  
WD = 2 mm  
Stage at Y = 86.413 mm

Signal  
Photo  
Pixel Size

Mag = 100.00 K X  
Stage at X = 75.943 mm

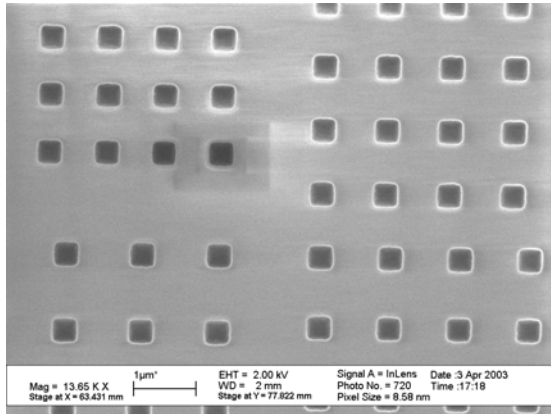
200nm  
EHT = 5.00 kV  
WD = 3 mm  
Stage at Y = 76.712 mm

Signal A = InLens  
Photo No. = 2098  
Pixel Size = 1.27 nm

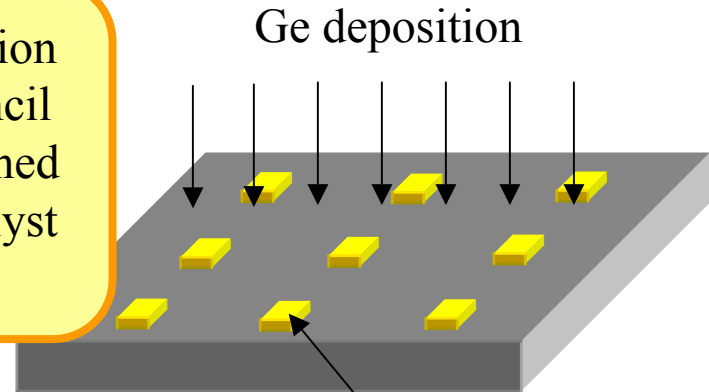
Date: 22 Jan 2004  
Time: 19:02



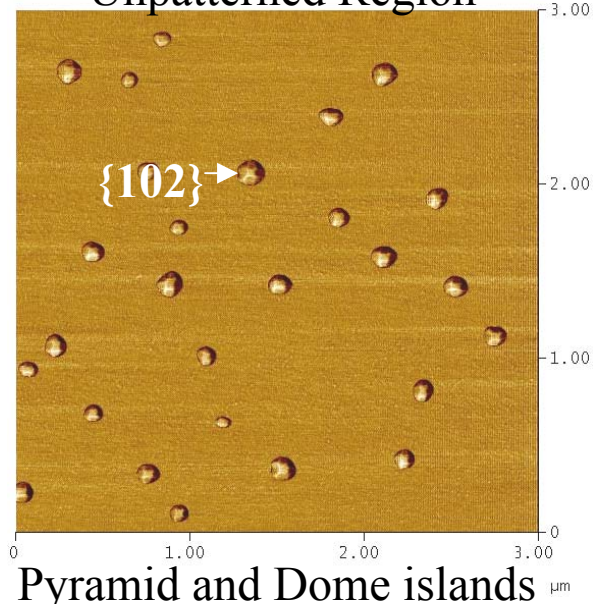
# Nanocrystal Catalyst Formation



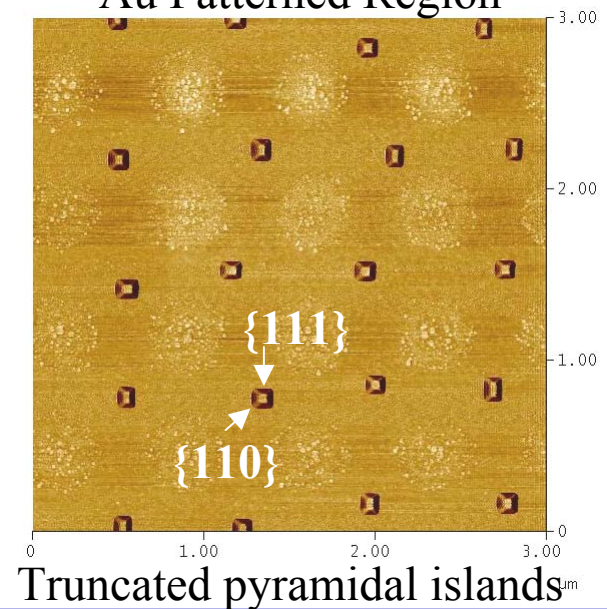
Au evaporation  
through stencil  
forms patterned  
growth-catalyst  
islands



Unpatterned Region

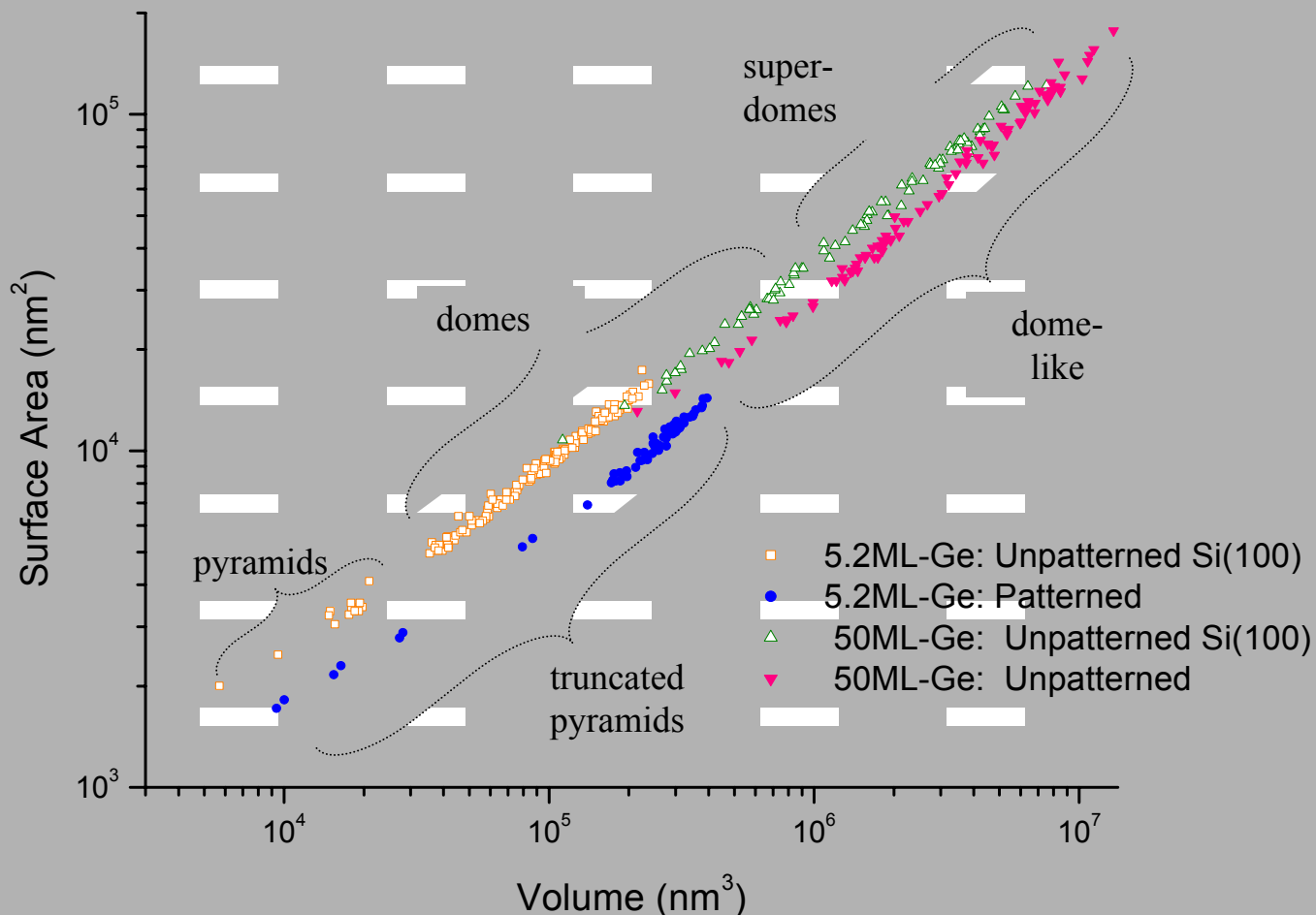


Au Patterned Region



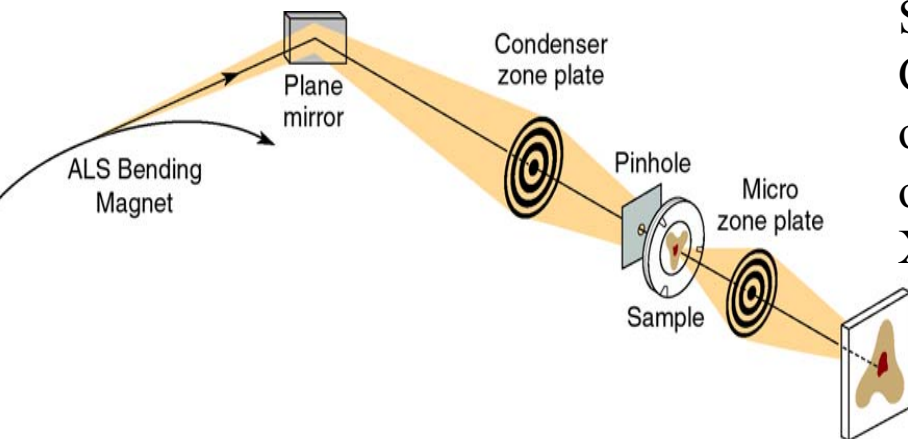
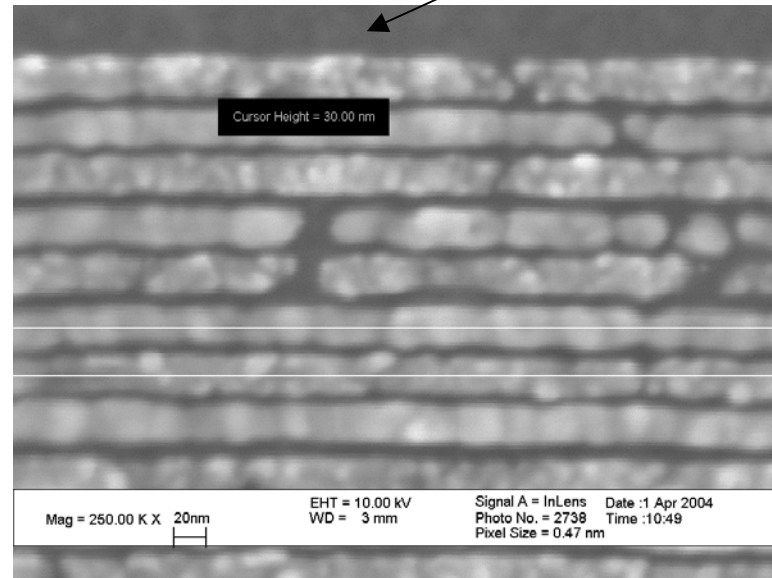
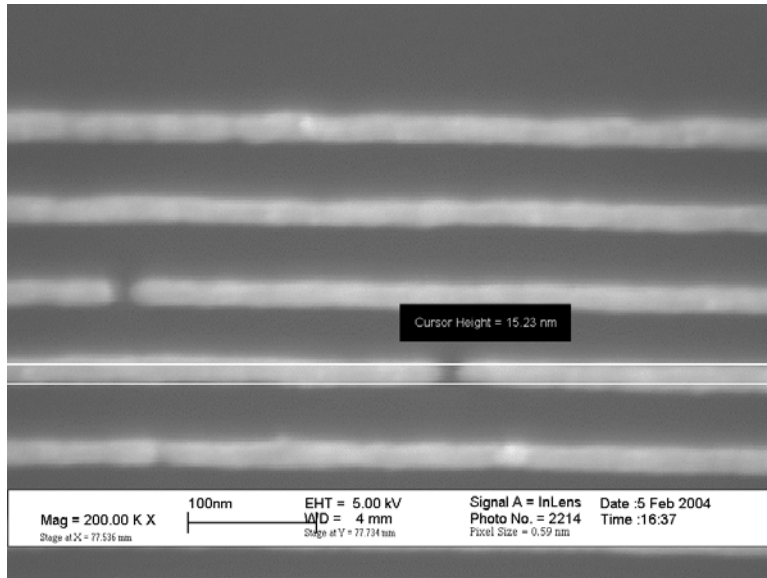
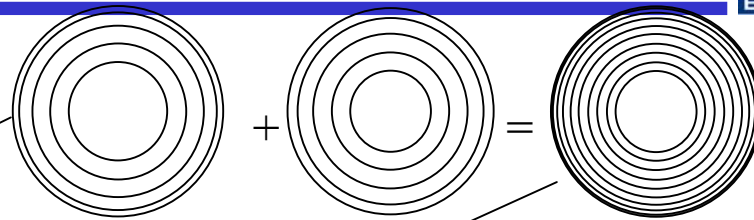


# Au-catalyzed growth: initial results

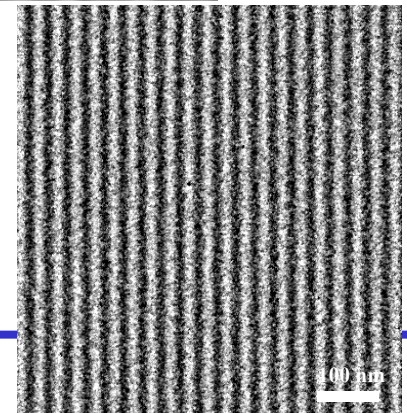


# 15 nm Zone Plates

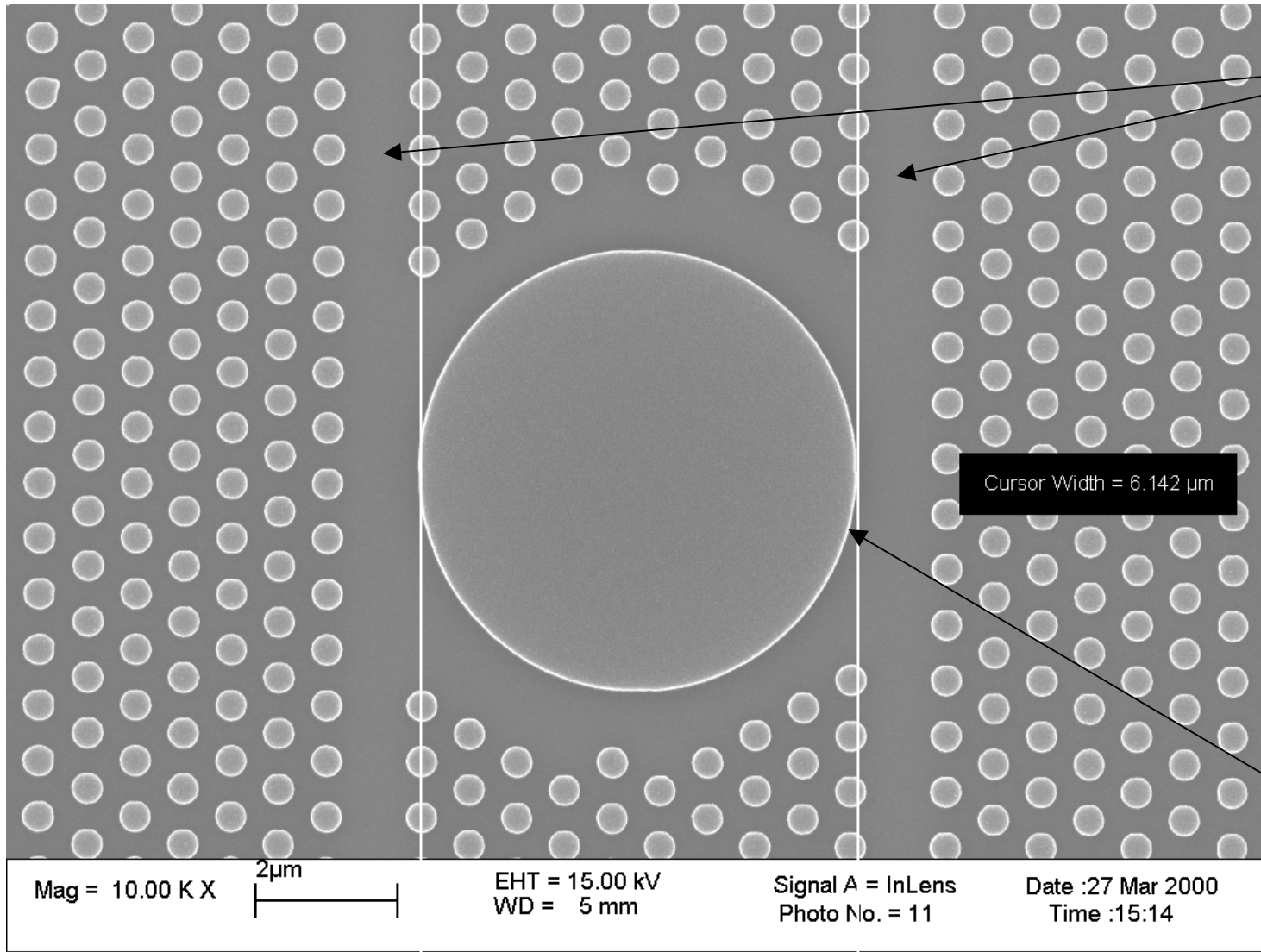
2 - 3 nm overlay permits interleaving of complementary exposures for ultra-dense nanofeatures



Soft x-ray image of a 15 nm Cr/ 15 nm Si multilayer test object taken at a wavelength of 1.5 nm ( $h\nu=815$  eV), by XM-1.



# Photonic Crystal Coupler: KRS



Waveguides

Lattice  
(Placement &  
CD control  
critical)

Resonator  
(CD control  
critical)

